

# Medium-modified fragmentation of b-jets tagged by a leading muon in ultrarelativistic heavy ion collisions

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## Abstract

The possibility to observe the medium-modified fragmentation of hard b quarks tagged by a leading muon in ultrarelativistic heavy ion collisions is analyzed. We have found that reasonable statistics,  $\sim 10^4$  events per 1 month of LHC run with lead beams, can be expected for the realistic geometrical acceptance and kinematic cuts. The numerical estimates on the effect of the medium-induced softening b-jet fragmentation function are given.

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# 1 Introduction

The experimental investigation of ultrarelativistic nuclear collisions offers a unique possibility of studying the properties of strongly interacting matter at a high energy density. In that regime the hadronic matter is expected to become deconfined and a gas of asymptotically free quarks and gluons is formed. This is a quark-gluon plasma (QGP), in which the colour interactions between the partons are screened owing to collective effects [1]. One of the important tools to study QGP properties in heavy ion collisions is a QCD jet production. Medium-induced energy loss of energetic partons, the so-called jet quenching, has been proposed to be very different in cold nuclear matter and in QGP, resulting in many challenging observable phenomena [2]. Recent RHIC data on suppression of inclusive high- $p_T$  charge and neutral hadron production from STAR [3], PHENIX [4], PHOBOS [5] and BRAHMS [6] are in agreement with the jet quenching hypothesis [7]. However direct event-by-event reconstruction of jets and their characteristics is not available in RHIC experiments at the moment, while the assumption that the integrated yield of all high- $p_T$  particles originates only from the jet fragmentation is not obvious.

At LHC a new regime of heavy ion physics will be reached at  $\sqrt{s_{NN}} = 5.5$  TeV where hard and semi-hard QCD multi-particle production can dominate over underlying soft events. The initial gluon densities in Pb–Pb reactions at LHC are expected to be significantly higher than at RHIC, implying a stronger partonic energy loss which can be observable in various new channels [8, 9, 10]. In particular, the influence of the medium-modified fragmentation of heavy quarks on dilepton spectra was analyzed in [11, 12, 13]. Since the estimated event rates for b quark production at LHC energies are expected to be high enough, in combination with high- $p_T$  jet production by gluon and light quark fragmentation this can give important information about the medium-induced effects for both light and heavy partons in nucleus-nucleus interactions at the LHC.

In previous paper [14] we analyzed the possibility to observe the medium-induced softening jet fragmentation function (JFF) of light partons tagged by a leading neutral or charge hadron in heavy ion collisions at the LHC. In this paper the possibility to measure the medium-modified b-JFF by a leading muon is suggested and analyzed for LHC conditions. In Sect. 2 we give the main definitions of JFF, calculate the cross section of  $B(\rightarrow \text{leading } \mu)$  production at LHC energies with PYTHIA generator and estimate the expected event rate for the realistic geometrical acceptance and kinematic cuts. Sect. 3 describes shortly a model of partonic energy loss in QGP used to evaluate the sensitivity of b-JFF to the jet quenching effect. Discussion on numerical results and summary can be found in Sect. 4.

## 2 $B(\rightarrow \text{leading } \mu)$ production at LHC

Let us recall that the jet fragmentation function  $D(z)$  determines the probability for a final “jet-induced” particle to carry a fraction  $z$  of the jet transverse momentum  $p_T^{\text{jet}}$ . In nuclear  $AA$  interactions JFF for leading particles can be defined as [14]:

$$D(z) = \int_{z \cdot p_{T \min}^{\text{jet}}} d(p_T^L)^2 dy dz' \frac{dN_{AA}^{\text{h(k)}}}{d(p_T^L)^2 dy dz'} \delta\left(z - \frac{p_T^L}{p_T^{\text{jet}}}\right) \Bigg/ \int_{p_{T \min}^{\text{jet}}} d(p_T^{\text{jet}})^2 dy \frac{dN_{AA}^{\text{jet(k)}}}{d(p_T^{\text{jet}})^2 dy}, \quad (1)$$

where  $p_T^L \equiv z p_T^{\text{jet}} = z' p_T$  is the leading particle transverse momentum,  $z'$  is the momentum fraction relatively to  $p_T$  of the parent parton (of course, without energy loss  $z = z'$  in the leading order of perturbative QCD),  $p_{T \min}^{\text{jet}}$  is the minimum threshold for energy of observable jets. The rate of  $k$ -type jets in mid-rapidity with transverse momentum  $p_T$  in  $AA$  collisions at the given impact parameter  $b$  is estimated as

$$\frac{dN_{AA}^{\text{jet(k)}}}{d(p_T^{\text{jet}})^2 dy}(b) = \int_0^{2\pi} d\psi \int_0^{r_{\max}} r dr T_A(r_1) T_A(r_2) \frac{d\sigma^{\text{jet(k)}}(p_T^{\text{jet}} + \Delta p_T^{\text{jet}}(r, \psi, \theta_0))}{dp_T^2 dy}, \quad (2)$$

and is determined by the absolute value of partonic energy loss as well as by the angular radiation spectrum. Here  $r_{1,2}(b, r, \psi)$  are the distances between the nucleus centers and the jet production vertex  $V(r \cos \psi, r \sin \psi)$ ;  $r_{\max}(b, \psi) \leq R_A$  is the maximum possible transverse distance  $r$  from the nuclear collision axis to the  $V$ ;  $R_A$  is the radius of the nucleus  $A$ ;  $T_A(r_{1,2})$  is the nuclear thickness function (see Ref. [15] for detailed nuclear geometry explanations). The effective shift  $\Delta p_T^{\text{jet}}(r, \psi, \theta_0)$  of the jet momentum spectrum depends on the jet angular cone size  $\theta_0$  (see Fig.1). In the leading order of perturbative QCD the jet production cross section,  $d\sigma^{\text{jet(k)}}/(dp_T^2 dy)$ , is calculated in our case with PYTHIA6.2 [16]. The rate of high- $p_T$  jet-induced hadrons is estimated as

$$\frac{dN_{AA}^{\text{h(k)}}}{d(p_T^L)^2 dy dz'}(b) = \int_0^{2\pi} d\psi \int_0^{r_{\max}} r dr T_A(r_1) T_A(r_2) \frac{d\sigma^{\text{jet(k)}}(p_T + \Delta p_T(r, \psi))}{dp_T^2 dy} \frac{1}{z'^2} D_k^{\text{h}}(z', p_T^2), \quad (3)$$

where the shift  $\Delta p_T$  of the hadron momentum distribution generally is not equal to the mean in-medium partonic energy loss due to the steep fall-off of the  $p_T$ -spectrum [17].

For jets initiated by light hadrons, the leading particles are the charged or neutral hadrons. However for heavy quark initiated jets there is the possibility to have a leading muon produced by semileptonic meson decays. Thus jet tagged by high- $p_T$  muon can be identified as a heavy quark jet. Note that  $\approx 20\%$  of  $B$ -mesons and  $\approx 12\%$  of  $D$ -mesons decay to muons, about half of the muons from  $B$ -decays being produced through an intermediate  $D$  [18].

We used PYTHIA6.2 [16] with CTEQ5L pdf parameterization to calculate the cross section of b-jet production and the corresponding spectra at  $\sqrt{s_{pp}} = 5.5$  TeV and to estimate the expected event rate for the realistic geometrical acceptance and kinematic cuts. To be specific, the geometry of Compact Muon Solenoid (CMS) detector is considered [19, 20]: the pseudo-rapidity coverage  $|\eta| < 3$  for jets and  $|\eta| < 2.4$  for muons. We define the muon as a leading particle if it belongs a hard jet and carries larger 20% of the jet transverse momentum. To be specific, the jet energy is determined here as the total transverse energy of the final particles collected around the direction of a leading particle inside the cone  $R = \sqrt{\Delta\eta^2 + \Delta\varphi^2} = 0.5$ , where  $\eta$  and  $\varphi$  are the pseudorapidity and the azimuthal angle respectively. Extra cuts  $p_T^\mu > 5$  GeV/ $c$  and  $E_T^{\text{jet}} > 50$  GeV were applied. Then the corresponding  $pp$  cross section for  $B(\rightarrow \text{leading } \mu)$  production is  $\approx 0.7$  pb, and Pb–Pb cross section is estimated as  $0.7 \text{ pb} \times (207)^2 \approx 0.03$  mb. The corresponding event rate in a one month Pb–Pb run (assuming 15 days of data taking),  $H = 1.3 \times 10^6$  s, with luminosity  $L = 5 \times 10^{26} \text{ cm}^{-2}\text{s}^{-1}$ , is  $N_{\text{ev}} = H\sigma_{PbPb}L \approx 2 \times 10^4$  in this case. Increasing the minimal jet energy results in reducing expected statistics, e.g. for  $E_T^{\text{jet}} > 100$  GeV the estimated rate is only  $\sim 10^3$  events.

### 3 The model for simulation of jet quenching

In order to test the sensitivity of b-JFF to the jet quenching, the following event-by-event Monte Carlo simulation procedure was applied (see Refs. [15, 21] for details of the model).

- Generation of the initial parton spectra with PYTHIA (fragmentation *off*).
- Generation of the jet production vertex at the impact parameter  $b$  according to the distribution

$$\frac{dN^{\text{jet}}}{d\psi dr}(b) = \frac{T_A(r_1)T_A(r_2)}{\int_0^{2\pi} d\psi \int_0^{r_{\text{max}}} r dr T_A(r_1)T_A(r_2)} . \quad (4)$$

- Calculation of the cross section  $\sigma = \int dt d\sigma/dt$  for scattering of a parton with energy  $E$  off the “thermal” partons with energy (or effective mass)  $m_0 \sim 3T \ll E$  ( $T$  is the medium temperature) and generation of the transverse momentum transfer  $t_i$  according to the distribution

$$\frac{d\sigma}{dt} \cong C \frac{2\pi\alpha_s^2(t)}{t^2} \frac{E^2}{E^2 - m_q^2} , \quad \alpha_s = \frac{12\pi}{(33 - 2N_f) \ln(t/\Lambda_{QCD}^2)} . \quad (5)$$

Here  $C = 9/4, 1, 4/9$  for  $gg, gq$  and  $qq$  scatterings respectively,  $\alpha_s$  is the QCD running coupling constant for  $N_f$  active quark flavors, and  $\Lambda_{QCD}$  is the QCD scale parameter which

is of the order of the critical temperature,  $\Lambda_{QCD} \simeq T_c \simeq 200$  MeV. The integrated cross section  $\sigma$  is regularized by the Debye screening mass squared  $\mu_D^2(T) \simeq 4\pi\alpha_s T^2(1 + N_f/6)$ . The maximum momentum transfer  $t_{\max} = [s - (m_q + m_0)^2][s - (m_q - m_0)^2]/s$  where  $s = 2m_0 E + m_0^2 + m_q^2$ ,  $m_q$  is the hard parton mass.

- Generation of the transverse distance between scatterings,  $l_i = (\tau_{i+1} - \tau_i)p_T/E$ :

$$\frac{dP}{dl_i} = \lambda^{-1}(\tau_{i+1}) \exp\left(-\int_0^{l_i} \lambda^{-1}(\tau_i + s) ds\right), \quad \lambda^{-1}(\tau) = \sigma(\tau)\rho(\tau), \quad (6)$$

where  $\tau$  is the proper time,  $\lambda$  is the in-medium mean free path,  $\rho \propto T^3$  is the medium density.

- Reducing the parton energy by collisional and radiative loss per scattering  $i$ :

$$\Delta E_{\text{tot},i} = \Delta E_{\text{col},i} + \Delta E_{\text{rad},i}, \quad (7)$$

where the collisional part is calculated in the high-momentum transfer approximation,

$$\Delta E_{\text{col},i} = \frac{t_i}{2m_0}, \quad (8)$$

and the radiative part is generated according to the energy spectrum  $dI/d\omega$  obtained in the frame of BDMS model [22] generalized to the case of heavy quarks – the “dead cone” approximation [23] (but note there are exist more recent developments on heavy quark energy loss in the literature [24, 25]):

$$\frac{dI}{d\omega}|_{m_q \neq 0} = \frac{1}{(1 + (l\omega)^{3/2})^2} \frac{dI}{d\omega}|_{m_q=0}, \quad l = \left(\frac{\lambda}{\mu_D^2}\right)^{1/3} \left(\frac{m_q}{E}\right)^{4/3}, \quad (9)$$

$$\frac{dI}{d\omega}|_{m_q=0} = \frac{2\alpha_s(\mu_D^2)\lambda C_R}{\pi L\omega} \left[1 - y + \frac{y^2}{2}\right] \ln |\cos(\omega_1 \tau_1)|, \quad (10)$$

$$\omega_1 = \sqrt{i \left(1 - y + \frac{C_R}{3} y^2\right) \bar{\kappa} \ln \frac{16}{\bar{\kappa}}} \quad \text{with} \quad \bar{\kappa} = \frac{\mu_D^2 \lambda_g}{\omega(1 - y)}, \quad (11)$$

where  $\tau_1 = L/(2\lambda_g)$ ,  $y = \omega/E$  is the fraction of the hard parton energy carried by the radiated gluon, and  $C_R = 4/3$  is the quark color factor. A similar expression for the gluon jet can be obtained by substituting  $C_R = 3$  and a proper change of the factor in the square bracket in (10), see Ref. [22]. The allowed range of values  $\omega_i = \Delta E_{\text{rad},i}$  in (10) is from  $\omega_{\min} = E_{LPM} = \mu_D^2 \lambda_g$ , the minimal radiated gluon energy in the coherent LPM regime, to initial jet energy  $E$ .

- Calculation of the parton transverse momentum kick due to elastic scattering  $i$ :

$$\Delta k_{t,i}^2 = \left(E - \frac{t_i}{2m_{0i}}\right)^2 - \left(p - \frac{E}{p} \frac{t_i}{2m_{0i}} - \frac{t_i}{2p}\right)^2 - m_q^2. \quad (12)$$

- Formation of the additional (in-medium emitted) gluon with the energy  $\omega_i = \Delta E_{\text{rad},i}$  and the direction relatively to the parent parton determined according to one of two possible simple parameterizations for the emission angle  $\theta$ : the “small-angular” parameterization,

$$\frac{dN^g}{d\theta} \propto \sin \theta \exp \left( -\frac{(\theta - \theta_0)^2}{2\theta_0^2} \right), \quad (13)$$

where  $\theta_0 \sim 5^\circ$  is the typical angle of the coherent gluon radiation estimated in [26]; or the “wide-angular” parameterization,

$$\frac{dN^g}{d\theta} \propto \frac{1}{\theta}. \quad (14)$$

- Halting the parton rescattering if 1) a parton escapes from the dense zone, or 2) QGP cools down to  $T_c = 200$  MeV, or 3) a parton loses so much energy that its  $p_T(\tau)$  drops below  $2T(\tau)$ .
- In the end of each event adding new (in-medium emitted) gluons into PYTHIA parton list and rearrangements of partons to update string formation are performed.
- Formation of the final particles by PYTHIA (fragmentation *on*).

The medium was treated as a boost-invariant longitudinally expanding quark-gluon fluid, and partons as being produced on a hyper-surface of equal proper times  $\tau$  [27]. In order to simplify numerical calculations in the original version of the model we omit the transverse expansion and viscosity of the fluid using the well-known scaling solution due to Bjorken [27] for a temperature and density of QGP at  $T > T_c \simeq 200$  MeV:

$$\varepsilon(\tau)\tau^{4/3} = \varepsilon_0\tau_0^{4/3}, \quad T(\tau)\tau^{1/3} = T_0\tau_0^{1/3}, \quad \rho(\tau)\tau = \rho_0\tau_0. \quad (15)$$

For certainty we used the initial conditions for the gluon-dominated plasma formation expected for central Pb–Pb collisions at LHC [28]:

$$\tau_0 \simeq 0.1 \text{ fm/c}, \quad T_0 \simeq 1 \text{ GeV}, \quad \rho_g \approx 1.95T^3.$$

## 4 Numerical results and conclusions

Figure 2 shows the b-JFF (1) of leading muons for the cases without and with medium-induced energy loss in central Pb–Pb collisions with the two parameterizations of the distribution on the gluon emission angles (13) and (14); the same geometrical acceptance and kinematic cuts as described in Sect. 2 were used. One can see the softening b-JFF due to partonic energy loss at  $z \gtrsim 0.4$ . The effect enhances with  $z$  decreasing (see Fig.3) and is more pronounced for the small-angular radiation. The reason for the latter fact is following. The contribution of the small-angular radiation to the total jet energy loss (due to “out-of-cone” partonic energy loss) is much lesser as compared with the broad-angular radiation. The former does not disappear totally mostly because not only leading (parent) parton, but all partons of a jet pass through the dense medium and emit gluons under the angles  $\theta$  relatively to their proper directions, which in general may not coincide with the jet axis (determined by the direction of a leading particle) and sometimes be even at the jet periphery. The broad-angular radiation increases the “out-of-cone” part of partonic energy loss and thus decreases the final jet transverse momentum  $p_T^{\text{jet}}$  (which is the denominator in the definition of  $z \equiv p_T^L/p_T^{\text{jet}}$  in JFF (1)) without any influence on the numerator of  $z$  and, as a consequence, in reducing effect on JFF softening.

Note that in the real experimental situation the jet observables will be sensitive to the accuracy of jet energy reconstruction in a high multiplicity environment, in particular, to the systematic jet energy loss. However, since the average reconstructed jet energy in Pb–Pb collisions is expected to be the same as in  $pp$  interactions (see section “Jet detection at CMS” in Ref. [8]), the short measure of jet energy will be the well-controlled systematic error for heavy ion as well for  $pp$  collisions, and it can be taken into account using the standard calibration procedure.

In summary, the channel with the muon tagged b-jet production in ultrarelativistic heavy ion collisions was first analyzed. The reasonable statistics,  $\sim 10^4$  events per 1 month of LHC run with lead beams, can be expected for the realistic geometrical acceptance and kinematic cuts. The effect on the medium-modified b-jet fragmentation was numerically studied for Pb–Pb collisions at the LHC. The significant softening b-jet fragmentation function determined by the absolute value of partonic energy loss and the angular radiation spectrum is predicted.

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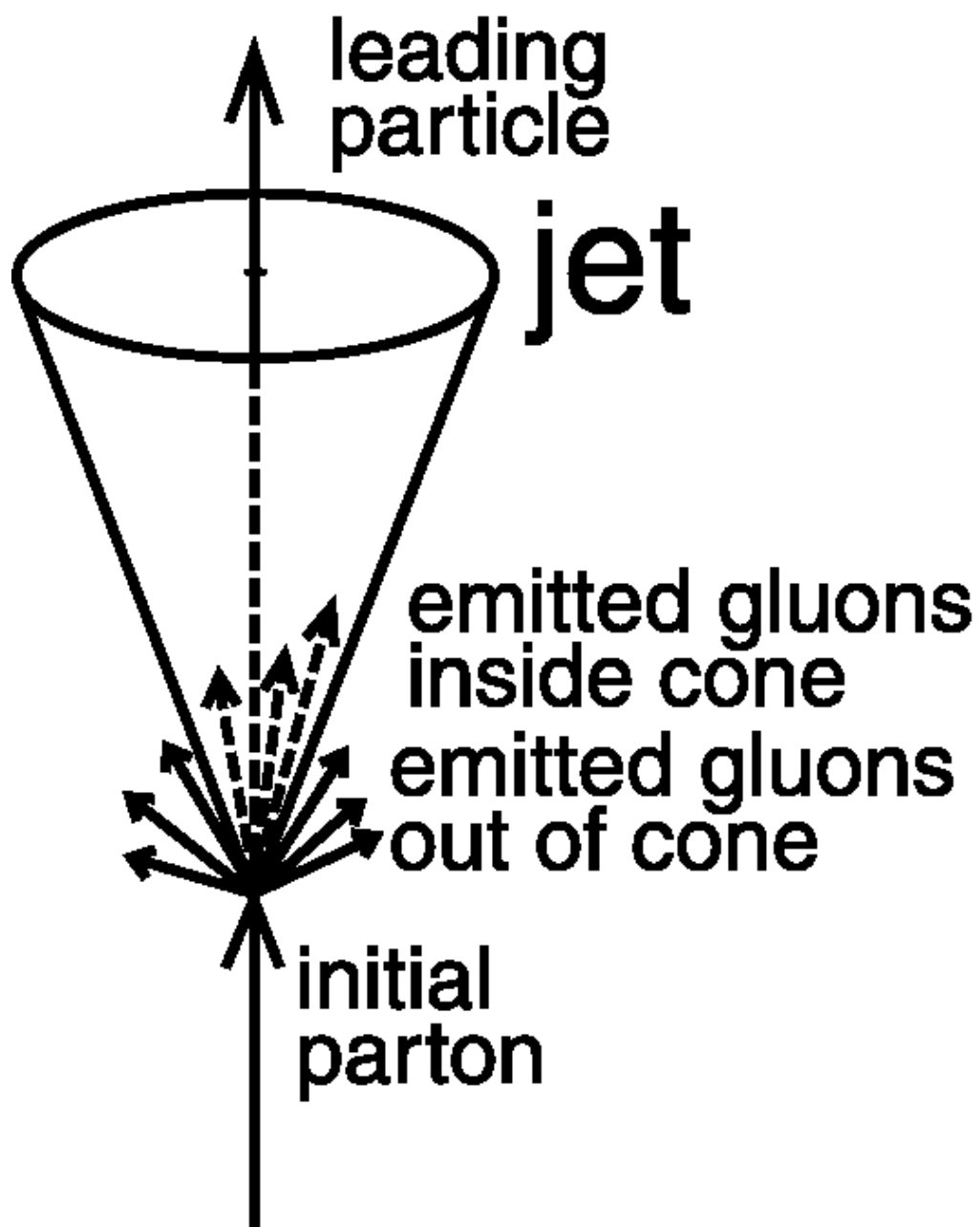


Figure 1: The schematic view of a jet with gluons emitted inside and outside jet cone.

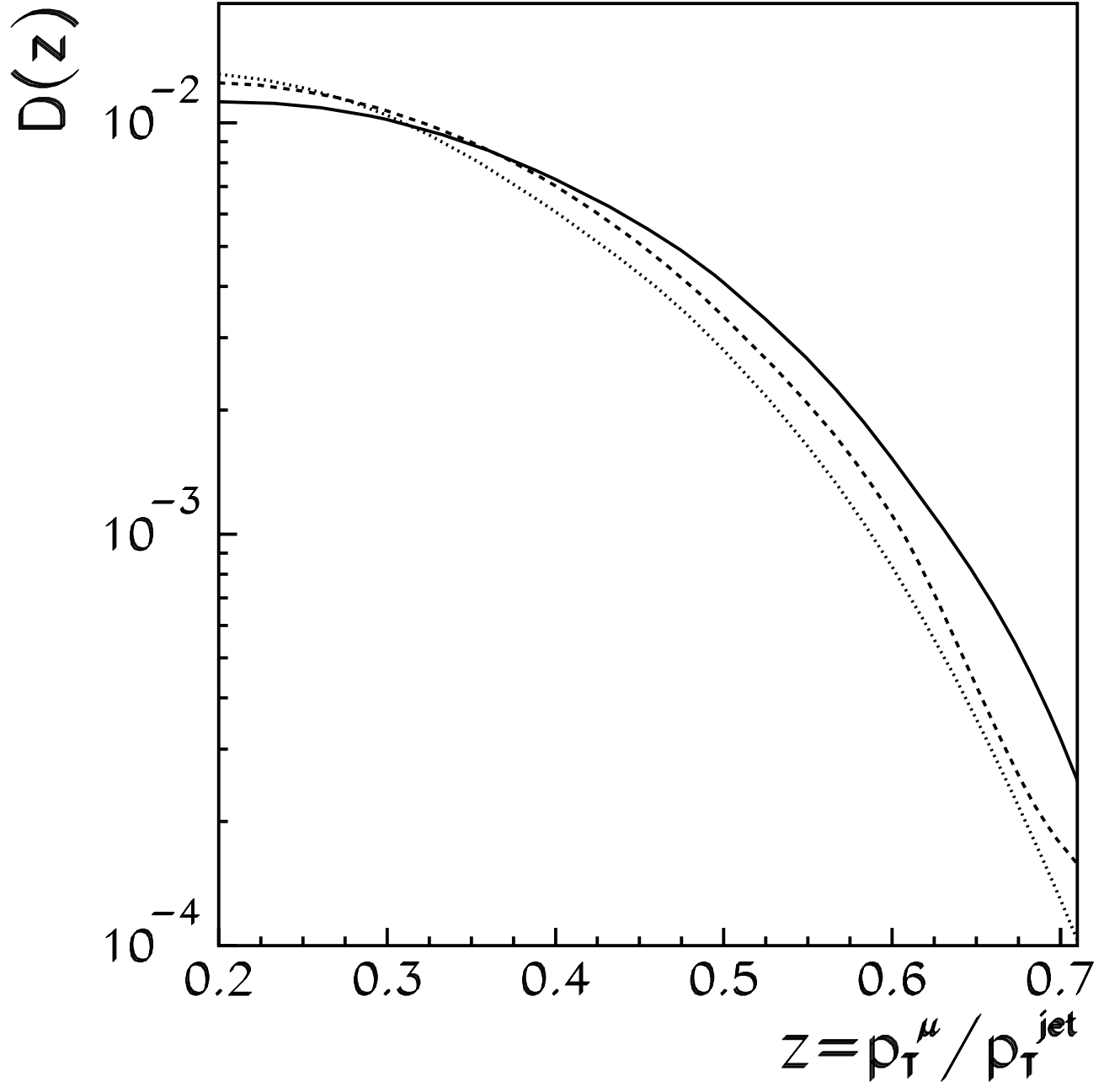


Figure 2: B-jet fragmentation function for leading muons without (solid curve) and with medium-induced partonic energy loss for the “small-angular” (13) (dotted curve) and the “broad-angular” (14) (dashed curve) parameterizations of emitted gluon spectrum in central Pb–Pb collisions. Applied kinematic cuts are described in the text.

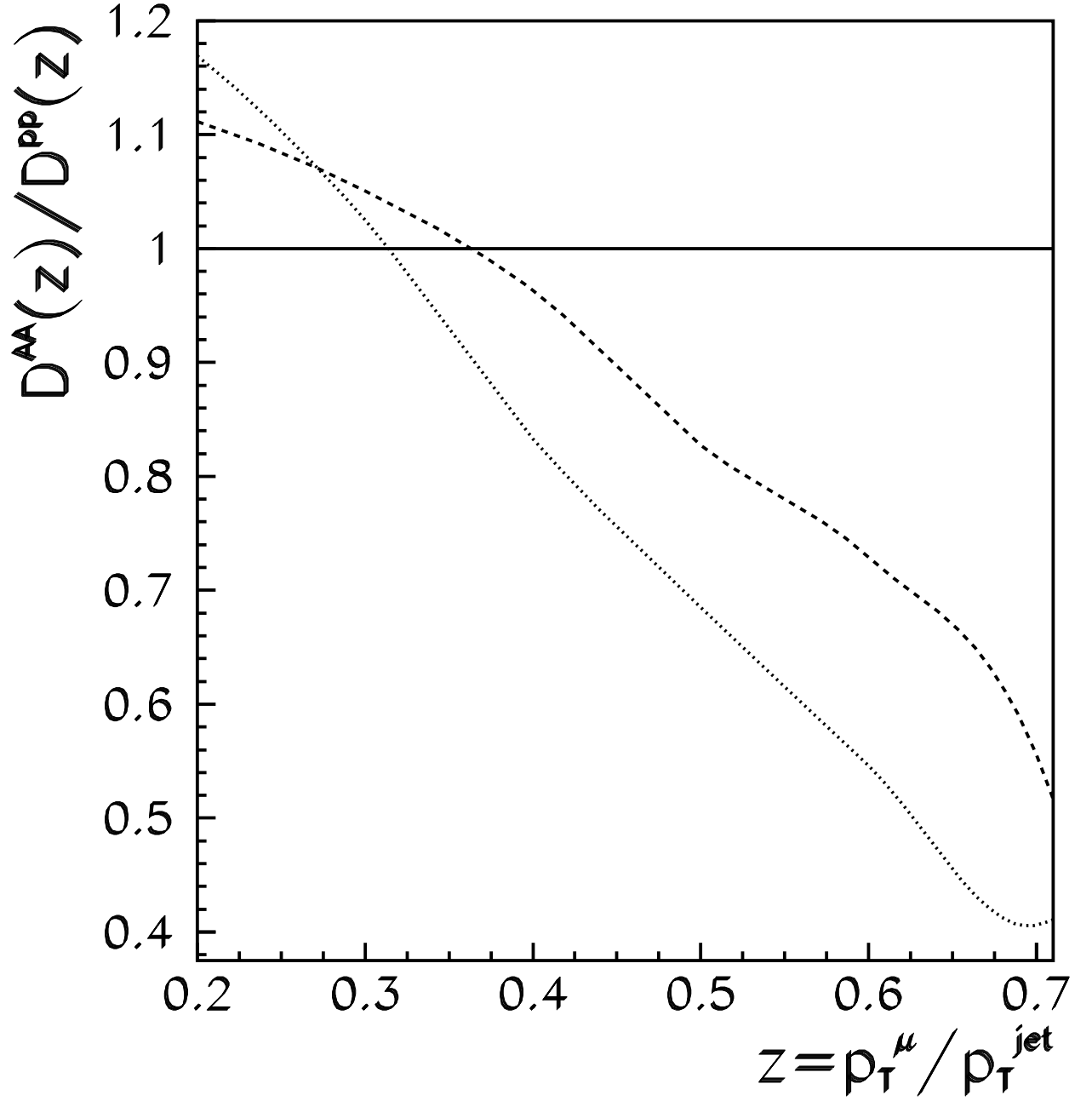


Figure 3: The ratio of B-jet fragmentation function for leading muons with energy loss to one without energy loss in central Pb–Pb collisions. The dotted curve is the result for the “small-angular” radiation, the dashed curve - for the “broad-angular” radiation. Applied kinematics cuts are described in the text.